ELECTRON TRANSPORT IN TA NANOLAYERS: APPLICATION TO TANTALUM CAPACITORS

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ABSTRACT

Tantalum pent oxide thin films are used as dielectric layers for capacitors, gate insulating layers for MOSFETS, RF MEMS switches, etc. Charge carriers transport mechanism and charge storage in insulating layer are important parameters for the application in these devices. Ta_20_5 films show good electrical and dielectric properties for considered applications and low leakage current density value $4x10^{-8}A/cm^2$ for the electric field 2 MV/cm. Dominant mechanism of charge carriers' transport is ohmic conduction for the low electric field, while Pool-Frenkel mechanism become dominant for electric field in the range 1 to 2.5 MV/cm. Tunneling current component is comparable with Pool-Frenkel current component or become dominant for electric field higher than 2 MV/cm at temperature lower then 200 K.

1. INTRODUCTION

A tantalum capacitor consists of metallic Ta anode, amorphous Ta_2O_5 insulating layer produced mostly by anodic oxidation, and semiconductor MnO_2 cathode. Capacitor structure can be in the first approximation considered as an ideal metal-insulator-semiconductor (MIS) structure [1 to 3]. Charge carriers transport mechanism and charge storage in insulating layer are important parameters for the application in these devices. Ta_20_5 films show good electrical and dielectric properties for considered applications and low leakage current density value $4x10^{-8}A/cm^2$ for the electric field 2 MV/cm. Dominant mechanism of charge carriers' transport is ohmic conduction for the low electric field, while Pool-Frenkel mechanism become dominant for electric field in the range 1 to 2.5 MV/cm. Oxide film contains oxygen vacancies with concentration of the order of $10^{18}/cm^3$. They act as donors - deep traps which are charged during the electric field application. Before VA characteristic measurement these traps where discharged. MIS structure model for tantalum capacitors with manganese dioxide cathode can be modified on the base of this leakage current analysis.

2. EXPERIMENT AND DISCUSSION

Experimental analysis in wide temperature range can give information on different current components as ohmic, Poole-Frenkel and tunneling. VA characteristics measured for tantalum capacitors from different producers in normal mode (Ta electrode is positive) and the temperature range 250 to 400 K were analyzed. The thickness d of the insulating layer for capacitors of producer A and B are in the range d = 30 to 33 nm. We will use value of relative permittivity $\varepsilon_r = 27$ for Ta_20_5 prepared by anodic oxidation. For the capacity C = 150 μF we obtain electrode area A = 211 cm^2.

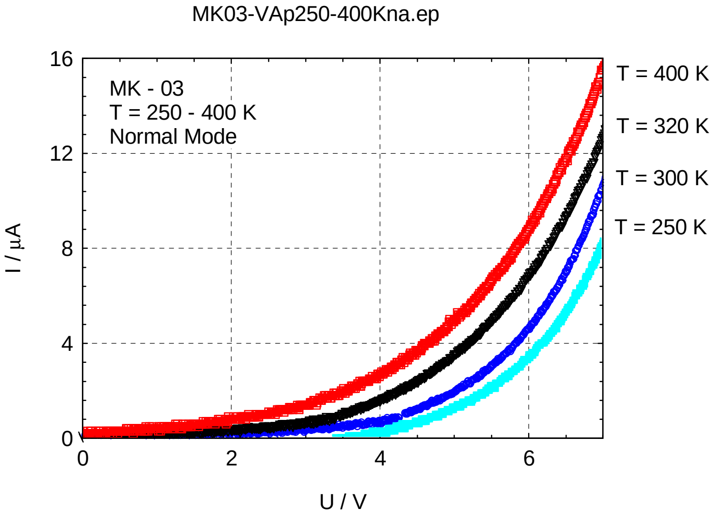

Fig. 1. VA characteristics of capacitor MK – 03 in normal mode, T = 250 - 400 K

VA characteristics of capacitor MK - 03 in normal mode for temperature range from 250 to 400 K are shown in Fig.1. It is clear from Fig.1 that leakage current increases with increasing temperature.

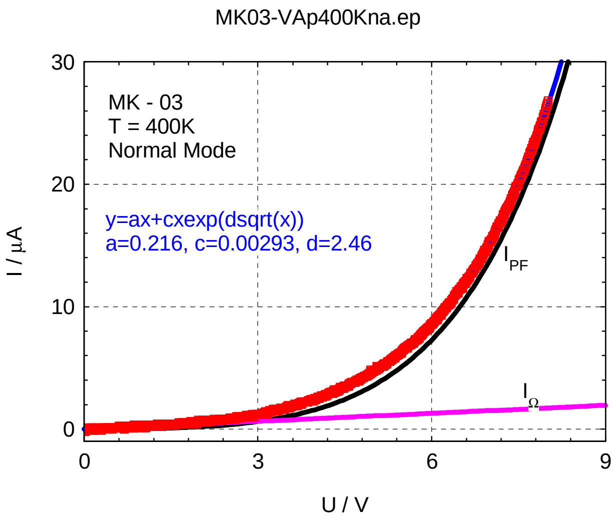

Fig. 2. VA characteristic of capacitor MK – 03 in normal mode, T = 400 K

The leakage current vs. applied voltage dependence can be approximated by equation:

$$I(t) = G_\Omega U + G_{PF} U \exp\left(\beta_{PF}\sqrt{U}\right) + G_T U^\alpha \exp\left(U_T / U\right), \quad (1)$$

Where G_Ω is ohmic conductivity, G_P is Poole-Frenkel conductivity, β_{PF} is Poole-Frenkel coefficient, G_T is tunneling current constant, exponent α depends on the potential barrier profile (α = 0 to 2), and U_T is a tunneling constant dependent on the barrier height and their thickness. Poole-Frenkel coefficient is given by:

$$\beta_P = (e^3 / \pi\varepsilon_0\varepsilon_r d)^{1/2} / kT\,, \qquad (2)$$

where d is the isolating layer thickness and ε_r is relative permittivity.

Ohmic and Poole-Frenkel current components are thermally activated, while the tunnelling current component is temperature independent as follow from [2]

$$U_T = (8\pi\sqrt{2m^*} / 3eh)(e\Phi_0)^{1.5} t_0\,, \qquad (3)$$

Where m^* is effective electron mass, h = 6.6x10 $^{-34}$ Js is Planck constant and eΦ_0 is the barrier energy in eV, and t_o is effective thickness of potential barrier.

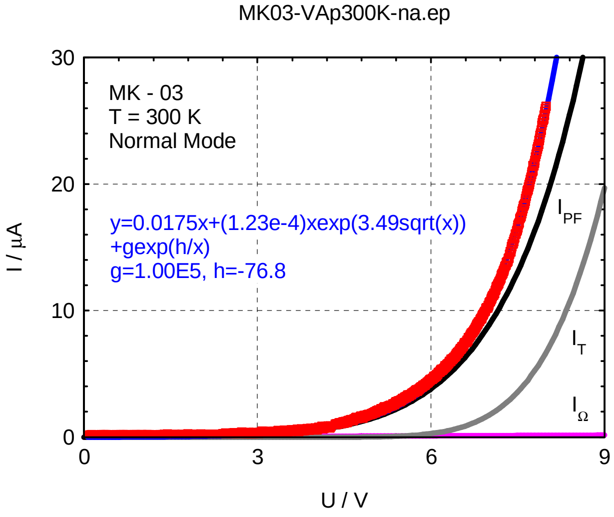

Fig. 3. Leakage current vs. applied voltage for capacitor MK03 in normal mode, T = 300 K

We have observed that the leakage current is given predominantly by the ohmic and Poole-Frenkel mechanism for the temperature higher than 300 K as is shown in Fig. 2 and Fig. 3.

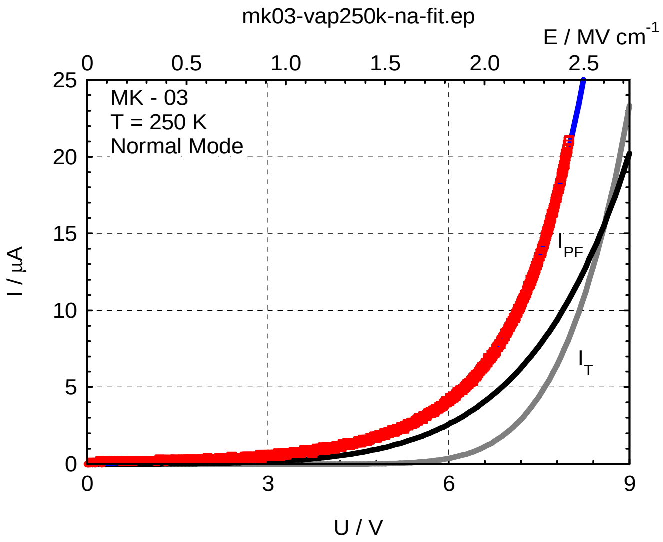

Fig. 4. Leakage current vs. applied voltage for capacitor MK03 in normal mode, T = 250 K

For the temperature 250 K the tunneling current is comparable with Poole-Frenkel current component for applied voltage 8 V as is shown in Fig. 4. In this case the applied electric field strength E is greater than 2.5 MV/cm.

To describe the quality of insulating layer we will give the dependence of current density as function of electric field strength which is shown in Fig.5. For capacitor MK03 we have maximum value of electric field strength E = 1.9 MV/cm at rated voltage U = 6.3 V. It is known [3] that breakdown voltage of amorphous Ta_2O_5 insulating layer produced by anodic oxidation is E_{BR} = 4 MV/cm. Using this value of break down voltage we can use this capacitor up to 12 V of rated voltage.

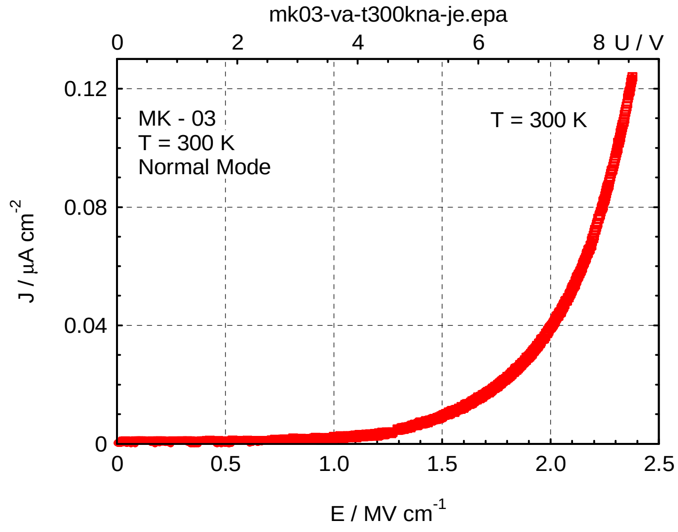

Fig. 5. Current density vs. electric field strength for capacitor MK03 in normal mode, T = 300 K

Poole-Frenkel coefficient β_{PF} depends on temperature, insulating layer thickness and relative permittivity. From temperature dependence of β_{PF} we can find value of insulating layer thickness or relative permittivity. Poole-Frenkel coefficient β_{PF} computed from our experiment in temperature range from 250 to 400 K is shown in Fig. 6.

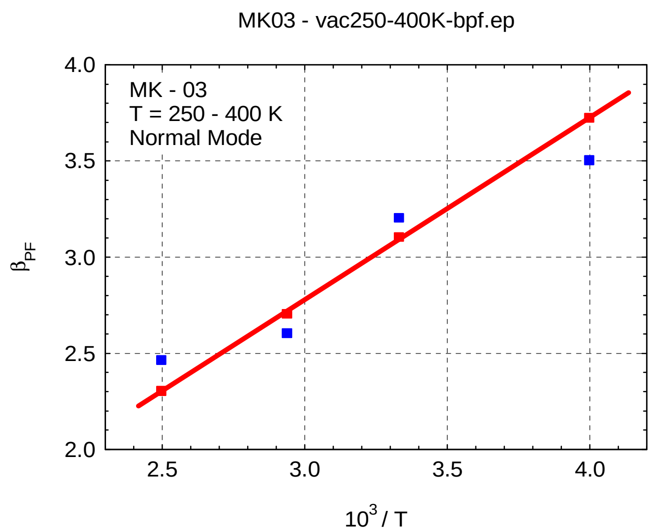

Fig. 6. Poole-Frenkel coefficient β_{PF} vs. reciprocal temperature for two different capacitors MK – 03

From the slope we have for insulating layer thickness d = 33.6 nm that relative permittivity is in the range ε_r = 25 to 31.

3. CONCLUSIONS

The leakage current value for the various temperatures and applied voltage are frequently used as the reliability indicator for tantalum capacitors. Leakage current provides information on the insulating layer thickness, its homogeneity and the number of defects in tested sample. In the insulating layer there are defects, which are responsible for the value and time evolution of the leakage current. The leakage current is a result of the random process of charge carrier transport and its DC component gives then information about the first statistical moment of this process.

1. Experimental analysis in wide temperature range can give information on different current components as ohmic, Poole-Frenkel and tunneling. It is clear that leakage current increasing temperature. Ohmic and Poole-Frenkel current components are thermally activated, while the tunnelling current component is temperature independent.
2. We have observed that the leakage current is given predominantly by the ohmic and Poole-Frenkel mechanism for the temperature higher than 300 K. For the temperature lower than 250K the tunneling current is comparable with Poole-Frenkel current component for applied voltage higher than 8V.
3. To describe the quality of insulating layer we give the dependence of current density as function of electric field strength. For capacitor MK03 we have maximum value of electric field strength E = 1.9 MV/cm at rated voltage U = 6.3 V.

ACKNOWLEDGEMENTS

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